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DEVELOPMENT AND APPROVAL OF A MATHEMATICAL MODEL OF A BRICK FIRING KILN

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A mathematical model that can be used to maintain the process parameters in real time as a function of the amount of brick manufactured is examined.

Russian manufacturers of ceramic brick are faced with the problem of not only improving product quality but also reducing fuel costs in the existing tunnel kilns built at the end of the last century based on Belorussian, Bulgarian, and German plans. These kilns were improved, had gas burners installed in the roof of the kiln, and an improved system of controlling the firing process. However, the heat exchange systems in the preparation zone and the cooling zone of these kilns were not totally suited to the physicochemical processes that take place in firing brick, and this caused excessive consumption of power for maintaining the necessary temperature conditions. This is seen from the equation for the process (operational) and real (production) temperature graphs (Fig. 1).

The real temperature graph was obtained with a MIKRON M90 L pyrometer and IMR-1500 gas analyzer in the kiln. A tunnel kiln from Al'tair Ceramics Co. (Izhevsk) with a capacity of 30 million units of brick a year was selected as the industrial sample. This kiln was installed in 1990 based on the standard Bulgarian plan. The kiln has a total length of 134.7 m, width of 3.5 m, height of 1.8 m, and is divided into 48 zones. The brick is heated by 94 Vulkan-gaz gas-flame burners installed in the kiln roof in the firing zone.

For maintaining competitiveness, these kilns unconditionally need to be updated by converting the entire firing process to an automatic regime based on modern technologies.

For solving this problem — increasing the efficiency of operation of tunnel kilns, improving the quality of the brick, and decreasing power consumption, we propose a mathematical model of a tunnel kiln which expresses the correlation between the input and output parameters of the firing process and mathematically describes it with systems of equations.

For constructing the mathematical model, we divide the entire kiln into 48 zones equal to process zones. We will assume that the temperature in each zone is constant, i.e., is not a function of time. The kiln's heat balance is a function of the thermal capacity of the gas burners, heat losses to the environment through the kiln's containment structures, the heat introduced or removed by stack gases, the charge of air-dried brick (fired brick) and cars.

The change in the temperature of the mixture of air and stack gases along the longitudinal section of the kiln channel is described by the heat balance equation in the i th zone:

$$c_p G_i^v T_i^g = c_p (G_i^v - G_{i+1}^v) T_{i+1}^g + P_i^G - Q_i^{\text{en}} - Q_i^k - Q_i^w, \quad (1)$$

where c_p is the heat capacity of the mixture of air and stack gases; G_i^v is the flow velocity of the air and stack gas mixture along the longitudinal section of the furnace channel; it is a function of the flow velocity of the air fed in for burning the gas, the flow velocity of the gas itself, and the flow velocity of the air fed into or taken out of the zone; T_i^g , $i = 1, N$ is the temperature of the gas in the zone; N is the number of zones.

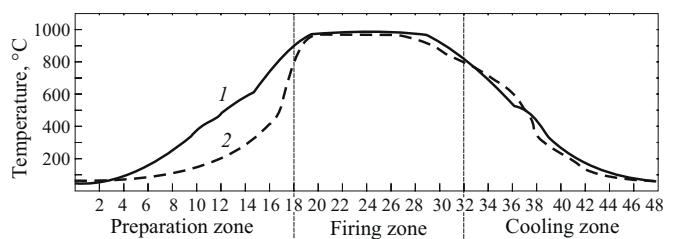


Fig. 1. Tunnel kiln temperature conditions: 1 and 2) process (operational) and production (real) temperature graphs.

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The left part of Eq. (1) is the heat flow carried by the hot gases through the boundary between the i th and $(i - 1)$ th zone.

The right part of the equation is represented by several terms.

The first term is the heat flow carried by the hot gases through the boundary between the i th and $(i - 1)$ th zone.

The second term P_i^G is the heat capacity of the gas burners. If there are no gas burners in the examined zone (preparation and cooling zones), this term is equal to zero.

Q_i^{en} are the heat losses to the environment through the kiln's containment structures.

Q_i^k is the amount of heat carried (taken away) by the brick charge.

The last term in Eq. (1), Q_i^w describes the amount of heat introduced (removed) by a car of mass M_w .

With respect to heat propagation, the brick and car are a homogeneous continuous medium.

The temperature fields of the brick and car are determined by the corresponding three-dimensional differential equations of nonstationary thermal conductivity without internal sources of heat in three spatial coordinates:

$$c_p \rho \frac{\partial T_j}{\partial t} = \lambda \left(\frac{\partial^2 T_i}{\partial x^2} + \frac{\partial^2 T_i}{\partial y^2} + \frac{\partial^2 T_i}{\partial z^2} \right), \quad (2)$$

where c_p , ρ , λ are correspondingly the heat capacity, density, and thermal conductivity of the substances (brick or car); $t \in [0, \Delta t]$ is the time (Δt is the pushing time, i.e., the time during which the charge is in the i th zone).

Let us write the initial and boundary conditions for this equation.

For the approximate solution of Eq. (2), the heated volume was divided into seven control volumes with temperatures T_j , $j = \overline{1, 7}$ and an implicit finite-difference scheme was written.

The system of difference equations is solved relative to unknown temperatures T_j , $j = \overline{1, 7}$.

For $t = \Delta t$, the average temperature is determined:

$$T_i^q = \frac{\sum_{i=1}^6 T_j^s + T_4^c}{7}, \quad (3)$$

where T_i^q is the temperature of the gas in the i th zone; T_j^s is the temperature of the surface of the brick in six planes; T_4^c is the temperature in the center of the brick.

Equations (1) and (3) are the general system of equations relative to unknown T_i for the gas, brick, and car, $i = \overline{1, N}$.

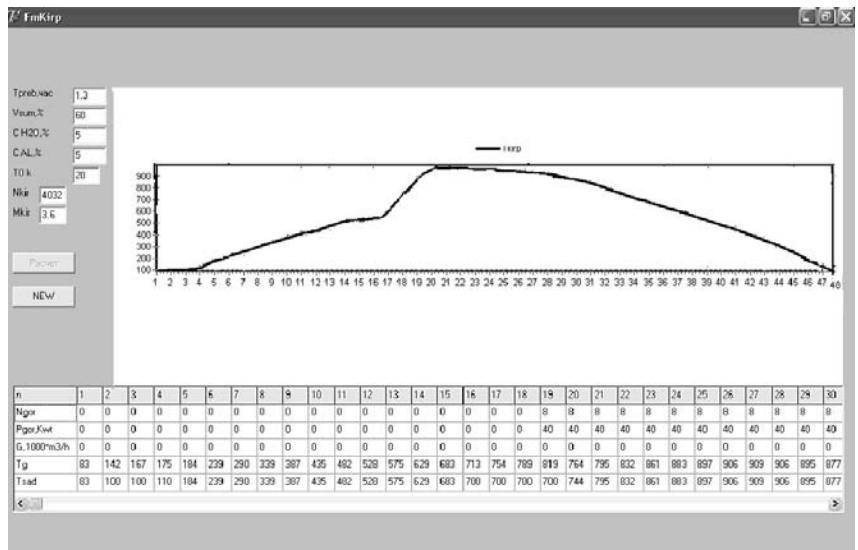


Fig. 2. Program window.

Equation (3) is used for calculating the temperatures in the brick and car while Eq. (1) is used for calculating the temperature of the air and stack gas mixture and are solved by an iterative (repetitive) method.

The charge temperatures by zones in a table and illustrated in Fig. 2 are the result of the calculations.

The initial data are input for performing the calculation: Tpreb is the pushing time; Gsum is the volume velocity of the stack gases, % of the maximum; CH20 is the water content in the brick; CAL is the aluminum content; T0k is the initial temperature; Nkir is the number of bricks in the charge; Mkir is the mass of the brick.

In addition, the following are introduced in the table for the corresponding zones: Ngor is the number of burners in the zone; Pgor is the power of the burner; G is the flow velocity of the air taken off or fed in.

The theoretical calculated temperature graph is in good agreement with the experimental graph, and as a consequence, the mathematical model satisfactorily reflects the real operation of the kiln.

The mathematical model allows obtaining the optimum temperature regime with minimal expenditure of energy and high quality of the brick.

To increase the firing quality and decrease the specific fuel consumption for firing, the process must be optimized and the optimum brick quality and power consumption ratio must be selected before updating.

The analysis of operation of the factory showed that in the last two years, the annual volume and product assortment are almost the same, but as a result of analyzing the kiln operating conditions, it was found that the rhythm and operating conditions of the kiln vary up to 10 times each month, which affected the quality of the brick and to a great degree excessive power consumption.

The rhythm and operating regime changed due to a change in the assortment of brick entering the kiln.

For stability of the firing process, it is necessary at the minimum to ensure constancy of the weight in the kiln. This is determined by the uniformity of the load of different kinds of brick over a month according to the output plan.

To optimize the firing process, according to the monthly plan, the furnace operating rhythm and regime are initially calculated with the mathematical model and the process parameters are selected, and then these changes are transferred to the kiln. This allows readjusting the kiln once a month,

which stabilizes the process, increases the quality, and decreases specific fuel consumption per product unit.

Recommendations for updating a kiln to optimize the firing process were given with the mathematical model:

increasing the brick heating temperature in the preparation zone according to the temperature conditions for firing the brick (process regulation) with additional side burners with defined power, number, and installation sites;

revamping the cooling zone according to the brick firing temperature regime (process regulation);

calculating the kiln design and control system to fit the defined output and quality level of the brick.